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# ROBUST FLUID FLOW AND PROPERTY MICROSENSOR MADE OF OPTIMAL MATERIAL

## BACKGROUND OF THE INVENTION

This is a continuation-in-part of U.S. Patent Application Serial No. 09/207,165, filed December 7, 1998, entitled "Rugged Fluid Flow and Property Microsensor," now U.S. Patent No. ____________, and U.S. Patent Application Serial No. 09/~~386,621,~~ 368,621 filed August 5, 1999, which is a Continuation-in-Part of U.S. Patent Application Serial No. 09/239,125, filed January 28, 1999, both entitled "Microsensor Housing".

Field of the Invention:

The present invention relates generally to thermal sensors of fluids, such as fluid flow sensors implemented in microstructure form. For convenience sake the term "flow sensor" will be used generically hereinafter for such thermal sensors. The reader will appreciate that such sensors may be utilized to measure primary properties such as temperature, thermal conductivity and specific heat; and that the heat transfers may be generated through forced or natural convection. The invention relates more specifically to a sensor of the Microbrick™ or microfill type having a central heating element and surrounding sensor arrays which are structurally robust and capable of operating in harsh environments. These Microbrick™ or microfill sensors include through-the-wafer interconnects thus providing very low susceptibility to environmental damage or contamination. The material of the sensor support structure is of thermal conductivity tailored to the application thus producing a more useful and versatile sensor, such as needed for high sensitivity or high mass flux fluid flow measurement or measurements in harsh environments.

Description of Related Art:

Open microbridge structures such as detailed in United States Patent 5,401,155, to Higashi et al., are well suited for measurements of clean gases, with or without large pressure fluctuations, since the microbridge structure is burst-proof. However, due to the open nature of

the microbridge structure, condensates from vapor can be uncontrollably retained in the microbridge structure leading to uncontrolled changes in its thermal response, or output, making the structure susceptible to output error and poor stability.

The typical microbridge structure has a silicon die wire bonded at the top surface to a header, or substrate, carrying further electrical leads and/or electronics. Typically, such wire for the wire bonds would be a one mil gold wire. This wire has a tendency to retain particles suspended in the fluid, retain liquid condensates, increase undesirable turbulence, and shift flow response. Due to its thinness, the wire is also susceptible to damage in a high mass flux environment, such as high rate liquid flow, and upon attempts to clean the sensor.

Membrane-based sensors overcome some of the problems of the microbridge structure because there is no opening exposed to the fluid. More specifically, there is no opening allowing the fluid to enter the underlying structure. However, because the membrane is sealed over an isolation air space and subject to differential pressure induced stress signal errors, membrane based sensors have limited application in high pressure applications. Due to the physical configuration of the membrane, it can deform or burst as pressure differences (on either side of the membrane) increase above 100 PSI (pressure levels that are very possible in high mass flux environments). The heating/sensing elements on the top surface of the membrane sensors are also typically wire bonded to other components, leaving the problems of the wire in the flow path accumulating debris and possibly breaking during cleaning attempts.

While many different materials may be used to make a fluid flow sensor, the choice of material can drastically affect the sensor's performance. A preferable material making up the sensor substrate would have a relatively low thermal conductivity among other characteristics. This low thermal conductivity is necessary to maintain the sensitivity for the sensor. With this relatively low thermal conductivity, all heating/cooling effects presented to the various sensing elements are caused predominatly by the fluid to be sensed. Stated alternatively, it is important to ensure that heat is not transmitted through the substrate excessively, resulting in signal shorts.

The micromembrane structure discussed above provides a design approach that enables accurate thermal measurements to be made in harsh environments (condensing vapors, with suspended particles, etc.). Specifically, the mass of silicon immediately below the heater/sensing

elements is greatly reduced or eliminated, thus limiting potential heat losses. Even in this structure, however, the selection of materials is critical -- low thermal conductivity and appropriate material strength continue to be very important. A disadvantage of this structure is its sensitivity to differential pressure (across its membrane) which induces a stress in the sensing elements and results in uncontrolled output signal changes or errors.

In addition to the above referenced thermal characteristics, it is highly desirable for the overall flow sensor to be chemically inert, corrosion resistant, highly temperature stable, electrically isolated, and bio-compatible. Obviously, many of these characteristics are achieved by proper selection of materials. Further, these desired characteristics are necessary in light of the sensors' operating environment. The materials chosen must provide for a sensor which is capable of operating in harsh environments.

It would therefore be desirable to develop a flow sensor which is not susceptible to the above referenced problems. Specifically, the sensor would not be affected by vapor accumulation beneath the microbridge, and would not have exposed bonding wire near the heating and sensing elements. The desirable sensor would be structurally robust and thus capable of operating in harsh environments. Further, it would be desirable to develop a flow sensor which is not affected by signal shorts, thus capable of sensing high mass airflows and liquid flows. To accomplish this a desired flow sensor would include a robust substrate or die with relatively low thermal conductivity, high temperature stability, high electrical isolation, corrosion resistance, chemical inertness, and biocompatability. The design of such a structure would enable flow rate and thermal property sensing over wide ranges at high pressure. Further, this capability would provide trouble free operation in hostile environments at a reasonable cost.

## SUMMARY OF THE INVENTION

The present invention details a microstructure flow sensor having a microsensor die with a Microbrick™ or microfill structure (each having a substantially solid structure beneath the sensing elements) and through-the-wafer electrical interconnections. Through the many benefits that are provided by this structure, a robust sensor can be created -- i.e. a sensor that is operable and accurate in many different applications, including harsh environments.

The sensor features a flat, passivated, top surface overlying the heater and sensor elements to provide appropriate electrical isolation. Further, the die, with its through-the-wafer interconnections, eliminates the need for bonding wires with their attendant problems as discussed above. In order to withstand a wide range of pressure levels and operate in harsh environments, the die structure is configured to be very robust. The die is made up of materials that have very low thermal conductivity, thus eliminating the possibility of undesired thermal signal shorts. For example, the die may be fabricated using various glass materials, alumina, or combinations of such materials.

The die is attached to a substrate having a suitably matched coefficient of thermal expansion (CTE) by any number of adhesives. Electrical contact is made by thermocompression bonding, solder bumping, conductive adhesives or the like. Preferably the through-the-substrate electrical contacts terminate in the necessary electrically conductive runs for attachment to further electronics of the sensor. This allows for easy interconnection to further devices.

The substrate may further have a passivation layer at the mating surface with the die in order to provide a fluid barrier to the bottom of the die and back fill seals to prevent access to the back-side contacts. Both silicon oxide and silicon nitride layers may be used in the construction of the die. The present invention will benefit the user by trouble free and reliable service in all fluid flow applications as well as being easily fabricated and easily subjected to cleaning maintenance.

The ability to perform high mass flux sensing operations is largely dependent upon the physical characteristics of the sensor. Most importantly, low thermal conductivity of the die substrate is necessary in order to create a sensor capable of operating in these high mass flux sensing situations. By minimizing the thermal conductivity, interference with sensor heating/cooling effects will be minimized and the sensing capabilities are enhanced. Specifically, the characteristics of the die substrate materials will control the proper route of heat transfer, avoiding transfer through the die substrate from the heater to the sensors. Various materials can provide this characteristic. Historically, silicon nitride of a microbridge sensor chip has been used to provide certain levels of thermal conductivity, while also being easily manufactured. However, its fragility prevents is use in harsh environments.

A more optimum material which exhibits the desired characteristic is glass. Glass, however, has not been previously used because it has not been easily micromachined. That is, it is difficult to form the required structures using glass. Another potential substrate material is alumina, which is widely used for electronics packaging and can be machined to serve as substrate with some desirable characteristics. One undesirable feature, however, is its high thermal conductivity, which would severely reduce the sensitivity of the sensor chip.

Recent developments in glass materials, including photosensitive glass and pyrex, have shown that micromachining is possible and extremely effective. Consequently, this material can now provide an alternate die substrate for a micromachined flow and property sensor. The present invention exploits the characteristics of glass (photosensitive glass, fused silica, etc.) or alumina materials to produce a flow and property sensor with optimized physical characteristics. Providing a glass based sensor in a Microbrick™ or microfill structure consequently enables the fabrication of a rugged sensor for sensing liquid properties or high mass flux fluid flow, without pressure-stress-induced error signals.

Due to the recent developments in glass, the use of this material as a die substrate generally reduces the amount of structural machining necessary. More specifically, the substrate can now be fabricated in a Microbrick™ or microfill structure which has a substantially solid structure. In this type of sensor die, the heating and sensing elements are placed directly on the substrate and no further processing or structuring is required beneath those elements. Consequently, the substrate itself is continuous beneath the sensing elements creating a more robust sensor die. The characteristics of the glass substrate material allows this Microbrick™ structure to be effectively used in harsh environments.

Alternatively, the same Microbrick™ structure can be achieved utilizing a plug type configuration. In this approach, a substrate material includes a hole under the heating and sensing elements or opening extending completely therethrough. This hole is then refilled with a filler or plug of appropriate materials creating a microfill structure (i.e. a micro hole filled with solid material). The combination of this substrate and the appropriate filler or plug can effectively tailor the thermal characteristics of the microsensor die. For example, the substrate

may be largely fabricated from alumina, and include a glass plug. The heating elements are then placed directly upon this plug element, thus providing the necessary thermal characteristics.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be more fully and completely understood from a reading of the Description of the Preferred Embodiment in conjunction with the drawings, in which:

Figure 1 is a top view of the microsensor die showing the micromembrane heater and sensing elements;

Figure 2 is a cross section of an assembled fluid flow sensor according to the present invention including a substrate structure;

Figure 3 is a more detailed view of the microsensor die and a substrate;

Figure 4 is a cross sectional drawing of an alternative microsensor die structure incorporating a filler portion;

Figure 5 is a cross sectional drawing of yet another microsensor die structure using a plug; and

Figure 6 is a schematic illustration of the backside processing required for one type of glass based sensors.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Throughout the Description of the Preferred Embodiment, like components will be identified by like reference numerals.

Referencing Figure 1, a fluid flow sensor die 21 includes a body 13. Onto body 13 are deposited sensor elements 15, 17 surrounding a central heating element 19; all composed of a suitable metal, such as platinum. The arrangement and theory of operation for a microstructure fluid flow sensor of this type is known to those in the art and will not be further elaborated on herein. Again, for convenience sake, this structure will be generally referred to as a "flow sensor," as indicated above.

Referencing Figure 2, a flow sensor according to the present invention may include a microsensor die 21 bonded to a substrate 23 having a suitably matched coefficient of thermal

expansion (CTE). Material for substrate 23 may include alumina, mullite, or known printed circuit board material having suitable CTE. A top surround body, or layer, 25 is placed on the substrate 23 to surround microsensor die 21 in order to further planarize the top surface of the sensing apparatus and provide minimal resistance to fluid flow and minimal crevices into which particles or condensates may lodge. The top surround 25 may be implemented as a epoxy layer, a preform, or any suitably constructed and arranged deposition or structural layer serving the above noted purposes. The joints between substrate 23, die 21, and top surround 25 may be further sealed or smoothed with a suitable epoxy or the like to remove potential dust and vapor traps.

As shown, microsensor die 21 comprises a body 13 having through-holes serving as electrical vias, collectively 29, filled with an electrical conductor material, preferable gold, chrome/gold alloy, or chrome/gold/palladium alloy. The use of through the way for interconnects, such as shown, provides many advantages for the flow sensor. Specifically, no wire bonds are extending upward from the upper surface of microsensor die 21. Consequently, there are no structures which interfere with the flow being sensed. As is expected, this eliminates any turbulence, along with avoiding stresses on the particular bonding structures.

Again, referencing Figure 2, the substrate 23 comprises a substrate body 55 comprised of alumina, mullite, or other known materials having coefficient of thermal expansion (CTE) suitably matched to the microsensor die 21. At the top surface of the substrate structure 23 which is to be mated with the silicon microsensor die 21 there is located a thermocompression solder-bump bond 51.

Silicon is often considered a very effective microsensor body material because it can be easily machined/processed using several well known silicon processing techniques. In certain applications, such as very high mass flux fluid flow sensing and high pressure applications, such silicon supported structures as microridges or mciromembranes do have certain disadvantages however. Specifically, the thermal isolation characteristics of silicon would limit structural and operational characteristics of a sensor if built directly on silicon. In order to deal with these thermal characteristics, the microsensor body of a silicon based sensor is configured in a micromembrane type structure, so as to limit the thermal mass below the heater and sensing

elements. Obviously, this limits the physical strength of a silicon based sensor. In addition, this micromembrane configuration is not suitable for high mass flux sensing because its output signal saturates before reacting high flux levels.

In order to effectively operate in harsh environments, the flow sensor must be structurally robust. As suggested above, the membrane structure, which burst near 100 PSI, does not exhibit the structural characteristics required to create a robust sensor. What is needed is a sensor robust enough to withstand high pressures due to sources (such as high pressure pulses, ultrasonic cleaning, and water hammer). In order to sense high mass flux flow rates, it is also necessary to have a substrate material with a thermal conductivity. If it is too low (as in the case of the membrane) the output signal saturates at moderate fluxes (~1g/cm$^2$s); but if it is too high the output signal becomes too small. Certain glass materials provide better thermal isolation characteristics (than silicon), thus increasing the sensing capabilities of the above-outlined micromachined flow and property sensor. The use of glass also allows for a more robust physical structure to be used. Additionally, the sensing elements will be protected by a passivation layer, thus reducing their sensitivity to vapors and liquids. These various characteristics result in a more versatile sensor which can be used in multiple applications. Furthermore, as outlined below, certain techniques provide for effective micromachining of glass based substrates.

Referring now to Figure 3, there is shown a more detailed structure for a glass based air flow or fluid flow sensor. The use of glass as a microsensor body material provides multiple features which enhance the capabilities of the sensor. These features include (1) the automatic electrical insulation for through-the-wafer contacts, (2) lower thermal conductivity than silicon, (3) environmental ruggedness needed to withstand pressure pulses as for sensing liquids, and (5) the ability to use a structurally robust sensor body configuration. Furthermore, the glass based sensor meets all requirements for chemical inertness, corrosion resistance, and biocompatability.

As mentioned above, glass provides inherent electrical isolation between various contacts. This is compared with a silicon based sensor where electrical isolation must be achieved by incorporating silicon dioxide layers on the substrate unless more costly silicon wafers are used that a grown to be slightly insulating. Obviously, this eliminates one layer of

material and one necessary processing step. This is particularly beneficial as the step of growing oxide is time consuming and done at fairly high temperatures.

Referring now to Figure 3, there is shown a cross sectional view of the glass based sensor die 121 of the present invention. While the sensor of the present invention is generally referred to as a glass based sensor, it is understood that other materials having appropriate physical characteristics could also be used. For example, alumina could be used as the base material for forming the sensor die 121. These other materials are intended to be within the scope and spirit of the present invention. A glass body 110 is used as the basis for forming sensor die 121. Upon the upper surface of glass body 110 is a layer of silicon nitride ($Si_3N_5$) 112 which again serves passivation and structural functions. Upon this passivation layer 112 there is constructed the heater element 114 and sensors 116, similar to those described above and well known by those skilled in the art. Once again, these heating and sensing elements can be fabricated from many materials, such as platinum. Covering the entire upper surface of the structure is a top layer 118 which serves as a protective passivation coating. Top layer 118 again is typically silicon nitride ($Si_3N_5$).

Similar to the sensor described above, glass body 110 has a plurality of electrical vias 129 extending therethrough. These electrical vias are typically holes that are created in glass body 110 and provide innerconnection to the backside 120 thereof. Again, this allows electrical connection to further elements of the sensing system. Fabrication of these electrical vias 129 is more fully explained with reference to Figure 4 below.

Placed within electrical vias 129 is a electrically conductive connecting material 131, which provides electrical connection to the actual heater 114 or sensor 116. The material used for these electrical connections is chosen to closely match the thermal expansion characteristics of glass body 110.

Once again, a substrate 123 is configured for attachment to the backside of microsensor die 121. Substrate 123 includes a substrate main body 155 made up of a material chosen to closely match the thermal characteristics of glass substrate 110. As an example, substrate 123 may be kovar-seal glass, alumina, PCB, etc. Upon the top surface of substrate body 155 is a glazing layer 160 along with a plurality of metal contacts 170. Various through holes or vias 180

can also be provided in substrate body 155 to provide appropriate electrical connection to further components.

In order to provide a operational sensor, sensor die 121 is attached to substrate 123 such that all appropriate electrical connections are properly aligned. This attachment can easily be achieved through thermal compression, or other appropriate attachment mechanisms much as solder bumping or z-axis adhesives.

As can be seen, glass body 110 is a substantially solid block of material. That is, other than the existing electrical vias 129 that are provided for electrical interconnection to components attached to the sensor die 121, there are no other openings or holes therein. Most significantly, the area of glass body 110 directly below heater 114 and sensing elements 116 is substantially solid. As can be expected, this provides an extremely easy structure to fabricate and minimizes the required processing steps. This type of structure can effectively be used due to the nature of the material chosen for body 110. More specifically, by utilizing a glass based material, having low thermal conductivity, an operational fluid flow sensor can be fabricated. This type of structure, commonly referred to as a Microbrick™, provides for a very robust and environmentally sound sensor. Most importantly, this sensor is able to withstand high pressure levels without bursting.

As mentioned above, the use of appropriate materials for glass body 110 makes the Microbrick™ structure possible. Generally speaking, this structure does not work well when silicon is used as the substrate material, due to its high thermal conductivity. Consequently in silicon, a heat transmission path is too easily created through the substrate material itself, resulting in unusually low/signal outputs. As mentioned above, this is highly undesirable for any fluid flow sensing as it diminishes the sensitivity of sensing elements 116 relative to heater 114.

Referring now to Figure 4, there is shown an alternative embodiment of the present invention. In this modified-micromembrane configuration, a microsensor die 221 is again based upon a glass body 210. As in the embodiment shown in Figure 3, a passivation layer 112 is deposited immediately upon the upper surface of glass body 210. Upon this passivation layer is fabricated a heater 114 and a pair of sensing elements 116. Also included are top surface interconnections 119 which provide electrical interconnects between the sensing elements and all

other appropriate components. Coated on top of these elements (heater 114, sensing elements 116 and interconnections 119) is a protective layer 118.

As can be seen, glass body 210 includes a central filler portion 212 below heater 114 and sensing elements 116. In this embodiment, filler portion 212 further enhances the operation of microsensor die 221 by providing additional thermal isolation between heater 114 and sensing elements 116. As mentioned above, the glass material chosen for glass body 210 provides many advantages and more optimal thermal isolation than silicon. However, glass does have some thermal conductivity characteristics, as do virtually all materials. The transit heating affects, as described above, are further reduced by utilizing a material in filler portion 212 which has thermal conductivity properties even better than glass. Consequently, the overall structure immediately adjacent heater 115 and sensing elements 115 has a very low thermal conductivity characteristic. Consequently, the sensitivity of the sensor at high mass flux fluid flow conditions is greatly enhanced.

Referring now to Figure 5, there is shown yet another configuration for a microsensor die 321. In this particular configuration, microsensor die 321 is based upon body 310 which is configured somewhat similarly to glass body 210 shown in Figure 5. However, in this instance, body 310 may be manufactured out of other materials including both glass or silicon or alumina. In order to further tailor the thermal characteristics of microsensor die 321, an appropriately configured plug 312 is utilized. Plug 312 extends completely or entirely through body 310 and is chosen from a material having desired thermal characteristics. As can be seen, heater 114 and sensing elements 116 are configured directly above plug 312. For example, body 310 may be configured from alumina while plug 312 may be configured of appropriate glass material. In this respect, a solid structure is maintained beneath heater 114 and sensing elements 116, while the thermal characteristics are again closely controlled.

The configuration shown in Figure 5 is particularly applicable when alumina or silicon is used as the body material. As is well known, alumina can be easily machined and manufactured into appropriate configurations using well known methods. Furthermore, alumina is more chemically inert than even glass or silicon. Consequently, the use of alumina alone has advantages in certain applications. Furthermore, alumina can be used in much higher

temperature applications as it is more temperature resistant. As mentioned above, using an appropriate plug material, the necessary thermal conductivity can be achieved resulting in a thermal sensor having the desired operational characteristics. This plug or microfill approach can similarly be used with other materials to appropriately "tune" or tailor the characteristics of the sensor.

Referring now to Figure 6, there is shown a block diagram of the backside processing to create the desired sensor die 121 of Figure 3. More specifically, Figure 6 schematically outlines the process used to appropriately configure glass body 110. Additionally, glass body 110 exists as a bare block of raw material (step 1). Next, in step 2, an appropriately configured mask 180 is placed on an upper surface of glass body 110. Mask 180 can be configured of a standard chrome material typically used with microstructure processing.

Next, the masked substrate is exposed to UV radiation 182. As is well known, UV radiation will not contact the masked areas of glass body 110, but will effect the unmasked portions. Specifically shown in Figure 6, the mask is configured to have five circular openings therein. Consequently, UV radiation is allowed to impinge on glass body 110 in those circular areas.

Next, in step 3, crystallization of the exposed areas is achieved. This crystallization facilitates the further processing of glass body 110. More specifically, the glass becomes etchable in the UV exposed areas. In step 4, this actual etching takes place wherein UV exposed areas are removed. This creates holes in glass body 110 which can then be further processed. In step 4, the through the wafer holes are metalized to allow electrical contact between the two surfaces. At this point, the backside processing is completed and glass body 110 can be further processed to ultimately create glass based sensor die 121.

Referring again to Figure 3, it can be appreciated that the front side processing necessary involves the creation of heater 114 and sensors 116 and all appropriate coating and connections. More specifically, an exemplary front side manufacturing process would be as follows:
(1) deposit passivation layer (silicon nitrate) 112 on the top side surface of glass body 110;
(2) deposit platinum on passivation layer to form electrical contacts and sensor/heating element;

(3) pattern the platinum coating and ion mill the platinum coating to result in the desired platinum pattern; and (4) lastly, deposit upper passivation layer 118 over entire structure.

As is well understood, a similar process can be used to manufacture components from Pyrex. These other processes may involve laser processing, chemical etching, or physical processing of the substrate to form the necessary holes.

It will be appreciated by the ordinarily skilled artisan that the present invention offers many advantages and that the detailed structure of the preferred embodiment presents several solutions to a myriad of problems. It will be recognized that various structures of the preferred embodiment may have counterparts substituted therefore when the unique advantages of that particular element are not desired for a selected sensor application. The present invention is thus only to be limited by the appended claims. Having thus described the invention what is claimed is: